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The Use of Stumps for Biomass in British Columbia A Problem Analysis

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BRITISH COLUMBIA

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Kirsten Hannam

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CONTENTS

1 Introduction 1

2 Soil and Site Sensitivity Interpretations for Stump Removal in British Columbia and Elsewhere 2

2.1 Stump Harvesting in Canada 2

2.2 Stump Harvesting in the United States and Europe 4

2.2.1 Finland 5

2.2.2 Lithuania 5

2.2.3 Sweden 5

2.2.4 United Kingdom 5

2.3 Ecosystem or Landscape-level Site Types in Which Stump Removal Is Discouraged 6

2.3.1 British Columbia 6

2.3.2 Finland 7

2.3.3 Sweden 7

2.3.4 United Kingdom 7

2.4 Soil or Stand-level Site Types in Which Stump Removal Is Discouraged 8

2.4.1 British Columbia 9

2.4.2 Finland 10

2.4.3 Sweden 11

2.4.4 United Kingdom 11

2.5 Guidelines for Stump Removal Practices 12

2.5.1 British Columbia 12

2.5.2 Finland 13

2.5.3 Sweden 14

2.5.4 United Kingdom 14

2.6 Guidelines for Stump Retention 15

2.6.1 British Columbia 15

2.6.2 Finland 15

2.6.3 Sweden 16

2.6.4 United Kingdom 16

2.7 Summary and Issues Raised 16

2.7.1 Stand productivity after stump harvesting 17

2.7.2 Simplification of method for assessing sensitivity to stump removal 20

2.7.3 Retention guidelines 20

3 Stump Harvesting and Utilization Technology 21
3.1 Harvesting and Transport within the Cutblock 21
3.1.1 Stump removal and site preparation 22
3.1.2 Innovations in harvesting heads 22
3.1.3 Innovations in forwarders 22
3.2 Transportation and Comminution 22
3.3 Utilization 24
3.4 Future Directions 24

4 Stump Content of Roadside Debris Piles 25

5 Methods of Estimating the Volume and Biomass of Tree Stumps and Roots 25
5.1 Above-ground Stump Volume 25
5.2 Above-ground Stump Biomass 25
5.3 Root Biomass 26

6 Conclusions 27

7 Literature Cited 28

TABLES

1 Summary of provincial stump and biomass harvesting guidelines in Canada 3
2 Summary of stump and biomass harvesting guidelines in United States and Europe 4
3 Ecosystem or landscape-level site types in which stump removal is discouraged 6
4 Summary of the stand-level site and soil conditions considered when assessing suitability for stump removal 8
5 Summary of the common factors considered in determining mass wasting, soil erosion, soil compaction, soil displacement, and forest floor displacement hazards in British Columbia 9
6 Stumping trials with published soil carbon and nutrient data, and tree growth and/or foliar nutrient data, from North America 18

In British Columbia, stump removal was first tested in 1968 as a method of reducing the spread of root disease into regenerating stands (Morrison et al. 1988). Over the last few decades, stumping, as it is also known, has been practiced throughout the province in forests infected with the root disease fungi *Armillaria ostoyae, Inonotus tomentosus,* and *Phellinus weirii* (Sturrock 2000). Given the growing interest in bioenergy in the province (Province of British Columbia 2008), and the increasing popularity of stumps as a feedstock for bioenergy plants in Europe (e.g., Bjorheden 2006; Hakkila 2006), it is timely to consider the viability of using stumps as an energy source in British Columbia.

Although stumping has been shown to improve forest establishment in the short term, possibly through the site preparation effect or by suppressing the spread of root disease, there is disagreement on whether stump removal should be used primarily as a tool to mitigate root disease infection or as a technique for acquiring forest biomass (e.g., Province of British Columbia 1995; Gibbs et al. 2002; Vasaitis et al. 2008; TAPIO 2010). In fact, the perception of stumps as a viable source of forest biomass varies strongly among jurisdictions. For example, there is general agreement that stump harvesting has the potential to reduce soil nutrient and carbon pools, remove critical habitat, cause soil disturbance (e.g., Quesnel and Curran 2000), and leave the soil susceptible to erosion and contamination, but there is little consensus on the ability of stump harvesting and retention guidelines to minimize or eliminate these risks (e.g., Egnell et al. 2007; New Brunswick Department of Natural Resources 2008; Forestry Commission 2009b; Benjamin 2010). In Finland, Sweden, and the United Kingdom, stump removal is considered to be an excellent method of site preparation, facilitating the movement of machine traffic during stand establishment and tending (Egnell et al. 2007; Forestry Commission 2009b; TAPIO 2010), while in British Columbia, planting near stumps is used as a silvicultural tool to protect seedlings from browsing and trampling damage, drought, and snow creep (Curran et al. 2000). In Finland, stump harvesting is believed to increase the diversity of ground vegetation (TAPIO 2010), but a greater concern in the United Kingdom is the increased potential for invasion by weedy species following stump removal (Forestry Commission 2009b). Other perceived benefits of stump harvesting include improved root architecture in the regenerating stand (Forestry Commission 2009b) and reduced seedling damage from pine weevils (*Hylobius abietus*) and black bark beetles (*Hylastes* spp.) (Egnell et al. 2007). Also, stump wood has a long storage life and high calorific value, and it produces chips that are more homogeneous than other sources of forest biomass (Walmsley and Godbold 2010). Nonetheless, the public perception of stump harvesting appears to be quite different in Europe and North America. In Scandinavia, stumps are a man-made unnatural substrate (Egnell et al. 2007; Dahlberg 2008), and their extraction and utilization receives widespread public support (Bjorheden 2006; Hakkila 2006; Egnell et al. 2007), while in Canada and the United States, stump harvesting is likely to be met with less enthusiasm (New Brunswick Department of Natural Resources 2008; Sustainable Forest Management Network 2008; Benjamin 2010). The use of stumps as a source of bioenergy is being strongly encouraged in

Finland as a means of reducing greenhouse gas emissions and improving energy security, but it is largely unprofitable even with considerable investment in technology, tax incentives, and government subsidies (Hakkila 2006; Stupak et al. 2007). Thus, considerable public and political "buy-in" will be required before stump harvesting is a viable option for British Columbia.

This problem analysis compares stump harvesting policies and practices in Europe and North America, addresses existing knowledge gaps, and proposes future areas of inquiry regarding stump harvesting for bioenergy production in British Columbia. The following topics are discussed in this problem analysis:

- soil and site sensitivity interpretations for stump removal in British Columbia and elsewhere
- stump harvesting and utilization technology
- stump content of roadside debris piles
- methods of estimating the volume and biomass of tree stumps and roots

2 SOIL AND SITE SENSITIVITY INTERPRETATIONS FOR STUMP REMOVAL IN BRITISH COLUMBIA AND ELSEWHERE

In order to facilitate comparisons among jurisdictions, the available guidelines from Canada, as well as those documents with relevant information from individual American states and European countries, are summarized in Tables 1 and 2, respectively.

2.1 Stump Harvesting in Canada

With the exception of New Brunswick, no Canadian province has developed specific guidelines for forest biomass harvesting, although they are being developed in Manitoba, Nova Scotia, Quebec, and Saskatchewan (Table 1) (Waito and Johnson 2010). In Ontario, existing forest harvesting guidelines undergo regular reviews to ensure that they address evolving issues, such as biomass harvesting (OMNR 2010). Policies relevant to biomass harvesting in Ontario, Quebec, New Brunswick, and Nova Scotia specifically prohibit the removal of stumps for energy production. In contrast, Saskatchewan's *Forest and Range Practices Act* includes stumps in its definition of timber, which suggests that stump material might be considered a commercial resource. No specific references to stump harvesting in Alberta or Newfoundland were located, although Alberta Sustainable Resource Development opposes intensive biomass harvesting in that province (B. White – Alberta Sustainable Resource Development, pers. comm., Feb. 13, 2011).

Only British Columbia has developed guidelines specific to stump removal, but they were prepared for the purpose of root disease management (Province of British Columbia 1995; Norris et al. 1998) and do not address issues associated with the removal of stumps off-site. Stump removal is being conducted on an experimental basis for root disease management in Manitoba, but the practice is not common there (I. Pines – Manitoba Conservation and Water Stewardship, pers. comm., Feb. 4, 2011), nor does it appear to be practiced in Ontario (D. Morris – Natural Resources Canada, pers. comm., Feb. 2, 2011) or Newfoundland (A. Arsenault – Natural Resources Canada, pers. comm., Feb. 8, 2011). Pushover logging to uproot infected stumps has

TABLE 1 *Summary of provincial stump and biomass harvesting guidelines in Canada*

Jurisdiction	References to stump removal in publications that address biomass or forest harvesting	Found specific guidelines for stump harvesting?	Found specific guidelines for biomass harvesting?
Alberta	–	No	No
British Columbia	"The recommended methods for removing the inoculum of all root diseases are **stumping** and push-over harvesting" (Prov. B.C. 1995).	Prov. B.C. 1995	No
Manitoba	"Removal of infected **stumps** is the recommended method for reducing the level of root rot inoculum on site" (Pines et al. 2004).	In process[a]	In process[b]
New Brunswick	"Do not remove the forest floor, including litter layer, soil surface, **stumps and root systems**" (NBDNR 2008).	No	NBDNR 2008
Newfoundland and Labrador	–	No	No
Nova Scotia	"Vendors shall not harvest or acquire fuel from coarse or fine woody debris, tree crowns, tops, or **stumps**" (NSDE 2010).	No	In process[b,c]
Ontario	"**Stumps and all below ground portions of a tree** are not available for utilization as a forest product" (OMNR 2010).	No	No
Quebec	"**Stumps and roots** are excluded from this definition [of forest biomass] . . . " (QMRNF 2009).	No	In process[d]
Saskatchewan	"Timber means **any trees or parts of trees** from Crown land, whether standing, fallen, cut, alive or dead" (Gov. Sask. 2007).	No	In process[b]

a Province of Manitoba 2006
b Waito and Johnson 2010
c NSDE 2010
d Thiffault and Morrissette 2009

been conducted on a small scale in Quebec (D. Paré – Natural Resources Canada, pers. comm., Feb. 4, 2011), but it is not a common practice.

Stump removal guidelines in British Columbia are older and less prescriptive than those from Europe, which are most concerned with the sustainability of forest biomass harvesting. Under the *Forest and Range Practices Act*, soil disturbance is permitted to exceed specified limits (5% on sensitive soils; 10% on non-sensitive soils) in order to remove infected stumps, provided that disturbed soils are then rehabilitated. Stump removal is not, therefore, prohibited on sensitive sites (Province of British Columbia 2004). In contrast, the *Soil Conservation Guidebook*, which pre-dates the *Forest and Range Practices Act*, acknowledges that pushover harvesting and post-harvest stump extraction will probably cause excessive soil disturbance, which will require some rehabilitation or mitigation measures, and it dictates that stump removal should not be conducted on sensitive soils (Province of British Columbia 2001). The review below concentrates on the guidelines that pre-date the *Forest and Range Practices Act* because they are still considered to be "best practices" for professional reliance.

2.2 Stump Harvesting in the United States and Europe

A number of U.S. states have developed biomass harvesting guidelines in recent years. In general, these guidelines recommend leaving stumps intact in the ground, although Alabama recommends avoiding stump harvesting on erosion-prone sites (Table 2). In Denmark, removal of stumps is not recommended. In France, although biomass harvesting guidance exists, no mention is made of stumps. In contrast, Finland, Lithuania, Sweden, and the United Kingdom have developed biomass harvesting guidelines that also address the removal of stumps for energy production under certain conditions.

TABLE 2 *Summary of stump and biomass harvesting guidelines in United States and Europe*

Jurisdiction	References to stump removal in publications that address biomass or forest harvesting	Found specific guidelines for stump harvesting?	Found specific guidelines for biomass harvesting?
	United States		
Alabama	"Avoid harvesting **stumps and root systems** in areas where it will cause excessive erosion"(Jetter 2010)	No	Jeter 2010
Maine	"Except where scarification of the soil is important for regeneration, leave the litter layer, **stumps, and roots** as intact as possible" (Benjamin 2010).	No	Benjamin 2010
Michigan	"Avoid removal of the forest litter layer, forest floor or below-ground biomass, including **stumps and roots**" (MIDNRE 2010).	No	MIDNRE 2010
Minnesota	" . . . biomass harvest might include the utilization of small-diameter trees or stems, snags, coarse woody debris, brush and **stumps** . . . [but we] generally recommend retaining coarse woody debris, snags and **stumps** . . . " (MFRC 2007).	No	MFRC 2007
Missouri	—	No	MDC 2009
Pennsylvania	"The forest floor, including roots, **stumps and below-ground biomass**, should always be off-limits to biomass harvesting" (PDCNR 2008).	No	PDCNR 2008
Wisconsin	"Do not remove the forest litter layer, **stumps, and/or root system**" (Herrick et al. 2009).	No	Herrick et al. 2009
	Europe		
Denmark	"Removal of **stumps** should be avoided" (Stupak et al. 2008)	No	Stupak et al. 2008
Finland	". . . energy wood . . . can be stemwood, **stumps**, or branches, potentially with needles or leaves included" (TAPIO 2010).	TAPIO 2010	TAPIO 2010
France	—	No	ADEME 2005
Lithuania	"Conclusions and guidance for **stump removal** . . . without negative effects on soil and ecosystems [were] compiled" (LNMMA 2008).	LNMMA 2008[a]	LNMMA 2008
Sweden	"**stumps** after logging operations . . . offer a biomass resource equally large or larger than branches and tops" (Egnell et al. 2007).	Skogsstyrelsen 2009[b]	Skogsstyrelsen 2002, 2008
United Kingdom	" . . . attention is now turning to the potential to utilize tree **stumps**" (FC 2009b).	FC 2009b	Nisbet et al., 2009

a Because the Lithuanian guidelines are not available in English, they are not discussed further.
b Guidelines are available in Swedish only, so Egnell et al. 2007 is used to inform the discussion of Swedish stump removal practices.

2.2.1 Finland Finland has the most well-developed system for harvesting stump biomass, and yet, the large-scale use of stumps for bioenergy production is only a recent phenomenon. Between 2000 and 2006, the use of stumps and roots as raw material for forest chips increased from 5000 m^3 to 458 000 m^3, and by 2008 had reached approximately 2 000 000 m^3 (Parviainen et al. 2008). Currently, stump harvesting is conducted only during final felling (i.e., not during thinning), for which stump removal guidelines have been developed (TAPIO 2010).

2.2.2 Lithuania The biomass and stump harvesting guidelines for Lithuania are not available in English and will not be discussed further. They were published after the Lithuanian guidelines for biomass harvesting were reviewed by Stupak et al. (2008).

2.2.3 Sweden Stump harvesting for bioenergy is also a recent development in Sweden. In 2008, few stumps were harvested pending the results of an environmental impact assessment, which began in the spring of 2008 (IEA Bioenergy Task 31. 2008). In 2009, the Swedish Board of Forestry gave permission for stump harvesting in a "controlled and responsible" manner: about 20 TWh of energy are now expected to come from stump biomass each year (Hektor 2009). Sweden recently published guidelines for stump harvesting (Skogsstyrelsen 2009). Given that the guidelines are not yet available in English, Egnell et al. (2007) is used as an indicator of the content of the Swedish guidelines. Stump removal is recommended only at final felling (Egnell et al. 2007).

2.2.4 United Kingdom In the United Kingdom, forest harvesting residues are increasingly being used to supply energy, and attention is now turning to using tree stumps, particularly in southern Scotland (Forestry Commission 2011). As in Finland and Sweden, stump removal is not conducted during thinning operations in the United Kingdom because of the risk of damaging adjacent trees, and stumping for biomass is performed only at final felling. The Forestry Commission recently published guidelines to assist the forest industry in identifying sites where stumps can be removed without compromising long-term site productivity (Forestry Commission 2009b). However, these guidelines do not apply to sites infected with *Heterobasidion annosum*, such as those found in East Anglia, where root disease reduction measures are considered to be a priority.

In summary, English-language versions of stump harvesting guidelines are available for British Columbia, Finland, and the United Kingdom, and an English-language summary of a Swedish discussion paper will be used in this review as a proxy for the Swedish stump harvesting guidelines. In order to simplify the comparison of stump removal guidelines from these jurisdictions, the discussion is divided into the following topics:

- ecosystem or landscape-level site types in which stump removal is discouraged;
- soil or stand-level site types in which stump removal is discouraged;
- guidelines for stump harvesting practices; and
- guidelines for stump retention.

2.3 Ecosystem or Landscape-level Site Types in Which Stump Removal Is Discouraged

2.3.1 British Columbia There are no specific prohibitions against stump removal based on ecosystem type in British Columbia. However, steep sites in wet biogeoclimatic zones (e.g., the Coastal Western Hemlock [CWH] zone) or wet site series within biogeoclimatic zones (e.g., the very wet, cold Engelmann Spruce–Subalpine Fir [ESSFvc] subzone) tend to be associated with higher mass wasting and soil erosion hazard ratings, which would preclude the removal of stumps from the ground (Province of British Columbia 1995; Curran et al. 2000). Furthermore, the *Armillaria* root disease management guidelines for the former Nelson Forest Region (Norris et al. 1998) suggest that pulled stumps should be left on-site in the Ponderosa Pine (PP) and Interior Douglas-fir (IDF) biogeoclimatic zones, and on mesic and drier site series of the Montane Spruce (MS), Engelmann Spruce–Subalpine Fir (ESSF) (dry cool [dk], dry cold [dc1]), and Interior Cedar–Hemlock (ICH)(very dry, warm [xw], and dry, warm [dw], and moist warm [mk1]) site series. This recommendation arose from the fact that pushover logging often entails bucking of stumps at the roadside, in contrast to post-harvest stumping operations, in which the stumps are generally left inverted in the stump hole (Norris et al. 1998; M. Curran – B.C. Ministry of Forests, Lands and Natural Resources, pers. comm., Feb. 24, 2011). In forests characterized by low soil organic matter contents and thin forest floors, the loss of stumps represents a substantial fraction of the total ecosystem carbon stock. Norris et al. (1998) suggest that pulled stumps should be retained within the stand on such sites. Taken together, these guidelines suggest that stump harvesting would be inappropriate in very dry or very wet biogeoclimatic zones or on steep slopes (Table 3), although stumps are not currently harvested for biomass in British Columbia.

TABLE 3 *Ecosystem or landscape-level site types in which stump removal is discouraged*

	British Columbia	Finland	Sweden	United Kingdom
Dry sites	PP and IDF; drier site series of the MS, ESSF, and ICH[a]	Dry heath[b]; craggy growing areas with boulders and lots of stones[b]	NA	Rankers, skeletal soils
Low-productivity sites		Barren heaths[b]; lingonberry turf heaths; stands suffering from nutrient deficiencies[c]	NA	Podzols, podzolic ironpans
Wet sites	CWH, MH, and wetter site series of the ESSF, ICH, and SBS[a] on steep slopes	Groundwater areas	NA	Peatland/bog soils, sandy soils with shallow water tables, gleys with > 25 cm surface peat

a The influence of biogeoclimatic zone and site series on site sensitivity to stump removal varies by (now defunct) forest region, and is used, along with slope gradient, soil texture, etc., when determining mass wasting and soil erosion hazard risk (i.e., biogeoclimatic zone is not the sole determinant of site sensitivity on wet sites). Biogeoclimatic zones: PP = Ponderosa Pine; IDF = Interior Douglas-fir; MS = Montane Spruce; ESSF = Engelmann Spruce–Subalpine Fir; ICH = Interior Cedar–Hemlock; CWH = Coastal Western Hemlock; MH = Mountain Hemlock.

b Stumps can be removed if there is an incidence of root rot in the area.

c Stumps can be removed if stands are supplemented with ash or boron fertilizer.

2.3.2 Finland In general, stumping in Finland is restricted to the most productive mesic sites, including mesic heaths and more fertile land, semi-dry heaths, and grassy and bilberry turf heaths (TAPIO 2010). Interestingly, semi-dry heaths, in which stump removal is allowed, are considered inappropriate for the removal of branches and crowns, whereas both logging residues and stumps can be removed from the other ecosystem types listed above (TAPIO 2010). Stump removal is considered inappropriate for wetlands, dry or barren heaths (unless root rot is present), sites with exposed boulders and stones, and stands suffering from nutrient deficiencies (Table 3) (TAPIO 2010). However, stump removal is allowed on sites considered to be nutrient deficient if the stands are then fertilized (TAPIO 2010).

According to the guidelines, stumps should be left on sites of natural or cultural interest, adjacent to leave trees and snags, and in buffer strips along waterways; however, the above-ground portion of the tree can be harvested within these areas (TAPIO 2010). There are also three levels of protected area in which differing intensities of stump removal are permitted: (1) stumps can be harvested from conservation areas (e.g., Natura 2000 areas[1]) as long as it is deemed appropriate by the local environmental authorities, (2) stumps cannot to be removed from valuable habitats described in *The Nature Conservation Act*, and (3) stumps can be removed from habitats of special importance described in *The Forest Act* as long as the important characteristics of the diversity of [these] habitats is safeguarded (Parviainen et al. 2008; TAPIO 2010).

2.3.3 Sweden Ecosystem types in which stump removal is not allowed may be identified in the formal guidelines (Skogsstyrelsen 2009), which have not, to date, been translated. However, Egnell et al. (2007) suggest that stump harvesting be restricted near sites of biological or historical significance, in watersheds "with high ambitions and goals for management" (presumably those used for municipal water supply, for example), in recreational areas near urban centres, near protected areas, or on reindeer herding grounds (because of the potential negative impact on the production of ground lichens).

2.3.4 United Kingdom Restrictions on stump harvesting in the United Kingdom are based primarily on soil type (Forestry Commission 2009b), which integrates the major factors (i.e., soil organic matter, nutrient availability, and moisture regime) considered in the stump harvesting guidelines from British Columbia and Finland (Table 3). Thus, the United Kingdom's guidelines consider skeletal soils and rankers (regosols), podzols and podzolic ironpans, and wetland soils to be sensitive to stump harvesting (Forestry Commission 2009b) (Table 3).[2]

1 All European Union Member States contribute to the network of Natura 2000 sites to protect the most seriously threatened habitats and species across Europe (www.natura.org).

2 For a brief description of the soil classification system in the U.K, refer to www.soilsworldwide.net/index.php/United_Kingdom_soil_classification_system. Useful information is also provided in Table 5 in Guidance on Site Selection for Brash Removal (Forestry Commission 2009a).

The guidelines also suggest leaving a buffer, within which stumps are left in place, around sensitive areas. These include sites that drain into freshwater "Special Areas of Conservation" or water bodies of "high ecological status," "priority and protected plant and animal species," and sites of historic significance, including veteran trees (Forestry Commission 2009b). However, the above-ground portion of the tree can be harvested within these buffer areas (Nisbet et al. 1997; Forestry Commission 2009a).

2.4 Soil or Stand-level Site Types in Which Stump Removal Is Discouraged

Table 4 summarizes the variables considered when assessing site suitability for stump removal in British Columbia, Finland, Sweden, and the United Kingdom.

TABLE 4 *Summary of the stand-level site and soil conditions considered when assessing suitability for stump removal*

	British Columbia	Finland	Sweden[a]	United Kingdom
Root disease infection	×	×		×
Soil moisture regime	×	×	×	× (via soil type)
Slope gradient and/or morphology	×	×		×
Soil texture	×	×	×	× (via soil type)
Coarse fragment content	×	×		× (via soil type)
Thickness of surface organic layers	×			×
Depth to water-restriction	×			
Depth to unfavourable subsoil or bedrock	×	×		× (via soil type)
Riparian areas	×[b]	×	×	×
Sites of natural or cultural interest		×	×	×
Unique considerations	Precipitation factor (BEC[c] zone and region), coarse fragment shape and arrangement		Reindeer herding areas, tree species composition, proximity to urban centres, forests to be burned	Worker safety

a This list is probably not complete given that the guidelines have not been translated into English.

b Riparian areas are not explicitly mentioned in the *British Columbia Root Disease Management Guidebook* (Province of British Columbia 1995), but subhygric to subhydric soils with < 70% coarse fragments have a very high soil compaction hazard rating, so it is unlikely that they would be considered appropriate for stump removal.

c Biogeoclimatic Ecosystem Classification

2.4.1 British Columbia The procedure described in the *Root Disease Management Guidebook* (Province of British Columbia 1995) for assessing the viability of stump removal for a given site begins as follows:

1. Conduct a survey of the stand to determine the level of root disease infestation, then stratify the stand into treatment areas for stump removal.
2. Evaluate terrain and soil sensitivity of the stand to determine the potential for detrimental soil disturbance.

Sensitivity to stump removal is determined by assessing the following hazards, summarized in Table 5 (Province of British Columbia 1995):

1. **Mass wasting** is "erosion by detachment and transportation due to gravity" and refers primarily to small-scale slope failures that cause on-site degradation (Curran et al. 2000). The risk of mass wasting (cut and fill hazard) is typically highest in the ICH, the wetter Sub-Boreal Spruce (SBS) and ESSF subzones, and the Boreal White and Black Spruce (BWBS) zones on glaciofluvial or glaciolacustrine terraces, steep glaciofluvial, colluvial, or morainal deposits, and in debris-filled channels or avalanche tracks (Curran et al. 2000). Mass wasting hazard (or terrain stability) is an important consideration when planning stumping operations because root removal may compromise soil strength and alter hydrological flow paths. In general, mass wasting hazard (or terrain stability) depends on the type of soil and surficial material (including soil texture), slope gradient, soil moisture regime (or soil drainage class), and regional climate, especially precipitation.

TABLE 5 *Summary of the common factors considered in determining mass wasting, soil erosion, soil compaction, soil displacement, and forest floor displacement hazards in British Columbia*

	Mass wasting	Soil erosion	Soil compaction	Soil displacement	Forest floor displacement
Reference	Prov. B.C. 2000	Prov. B.C. 1999a	Prov. B.C. 1999a	Prov. B.C. 1999a	Prov. B.C. 2000
Precipitation factor	×	×			
Soil moisture regime	×		×		
Slope gradient and morphology	×	×		×	×
Soil texture	×	×	×		×
Coarse fragment content	×	×	×		×
Thickness of surface organic layers				×	×
Depth to water-restricting layer		×	×		
Depth to unfavourable subsoil				×	×

2. **Soil erosion** is "the wearing away of the surface soil by water and wind," which can reduce site nutrient capital, stand productivity, water quality, and habitat quality (Province of British Columbia 1999a; Curran et al. 2000). Soil erosion hazard ratings depend on precipitation factor (Appendix 4 in Curran et al. 2000), slope gradient and length, depth to water-restricting layer, soil texture at the surface and in the subsoil, and the coarse fragment content of the top 15 cm of soil (Province of British Columbia 1999a). Many terrain stability maps also include an assessment of "soil erosion potential," although it is a less site-specific assessment of soil erosion hazard (Province of British Columbia 1999b).
3. **Soil compaction** is "the increase in soil bulk density that results from the rearrangement of soil particles in response to applied external forces" (Province of British Columbia 1999a). Soil compaction hazard ratings depend on moisture regime, and on the texture and coarse fragment content of the top 30 cm of soil.
4. **Soil displacement** is "the mechanical movement of soil materials by equipment and logs" (Province of British Columbia 1999a). Soil displacement can result in the exposure of unfavourable subsoils (e.g., dense or compacted soils, coarse soils with low nutrient contents, or calcareous soils), nutrient loss or redistribution, and altered hydrology. Soil displacement hazard ratings depend on slope gradient and complexity, depth to unfavourable subsoil materials, and depth of surface organic layers (Province of British Columbia 1999a).
5. **Forest floor displacement** is "the mechanical dislocation of the upper organic materials by equipment and movement of trees or logs," which can result in the redistribution of nutrients, exposure of unfavourable rooting medium, and losses in productivity (Curran et al. 2000). Forest floor displacement hazard reflects the relative importance of surface organic matter, including roots, in the total organic matter and nutrient capital of the soil. Sites with a high forest floor displacement hazard are typically nutrient poor, with a shallow forest floor layer. Forest floor displacement hazard ratings depend on forest floor thickness, mineral soil coarse fragment content, soil texture, depth to unfavourable subsoil, slope gradient, and surface terrain features (Appendix 5 in Curran et al. 2000).

For each of the five hazards described above, ratings can range from "Low" or "Very Low" through "Moderate" to "High" or "Very High." In general, stumping is recommended only for sites with a "Very Low" to "Moderate" hazard rating. The recommendations do suggest, however, that after consultation with a regional soil scientist, stump removal may be possible on sites in which only one of the hazard ratings exceeds desirable levels (Province of British Columbia 1995; Norris et al. 1998).

2.4.2 Finland Finnish guidelines suggest that stump harvesting be avoided on steep slopes with fine sand or silty soil textures; in rocky, shallow (< 50 cm) soils; adjacent to waterways or in wetland hollows; in sites of natural or cultural interest; or adjacent to leave trees and snags (TAPIO 2010).

2.4.3 Sweden Recommendations in Egnell et al. (2007) suggest avoiding stump harvesting on wet or fine-textured soils and in stands dominated by species other than Norway spruce (*Picea abies*) or Scots pine (*Pinus sylvestris*).

2.4.4 United Kingdom Sites considered to be most at risk from stump harvesting are steep or poorly drained sites with nutrient-poor, carbon-rich, and/or acidic soils. Stump harvesting is not recommended for slopes > 20°. As mentioned above, in the United Kingdom, formal assessments of site sensitivity to stump harvesting are based largely on soil type. As a result, site sensitivity determinations for sites with slopes < 20° require a good understanding of the Forestry Commission's soil classification system and information on the dominant soil types within the stand (i.e., those occupying > 20% of the stand), although small areas of highly sensitive soils (particularly those that can deliver sediment to watercourses) must also be considered in site plans (Forestry Commission 2009b).

In the United Kingdom, the first step in determining site sensitivity to stump removal is to consider the risk of the following four disturbances:

1. **Ground damage** is "increased soil damage due to compaction, rutting and disturbance leading to erosion and increased turbidity and siltation of local watercourses." Slopes > 20° are considered to be vulnerable to ground damage, as are peatland or bog soils; deep, peaty gleys; and littoral sandy soils with shallow water tables. Other soils types are considered to have a low to medium risk of ground damage (Table 1 in Forestry Commission 2009b).
2. **Soil carbon loss** is "increased carbon loss due to stump removal and soil disturbance, leading to reduced carbon stock" in the soil. Given the lack of empirical data on the implications of stump removal on the decay of soil organic matter, the guidelines make the assumption that the quantity of carbon lost from the soil as the result of stump removal will be proportional to the pre-harvest carbon content of the soil (Forestry Commission 2009b). Thus, low-carbon soils, such as brown earths (Brunisols) and skeletal soils, are classified as low risk to soil carbon loss, while soils with > 45 cm of surface peat are considered to be high risk. The guidelines also suggest that more rapid revegetation on stumped sites will promote carbon sequestration and offset some of the carbon losses associated with stump removal.[3] Unlike ground damage, soil infertility, and acidification, soil carbon loss is not directly considered when assessing site sensitivity to brash[4] removal (Forestry Commission 2009a).
3. **Soil infertility** is the "removal of essential major and micronutrients (e.g., nitrogen, phosphorus, potassium, and boron), leading to lower soil fertility and potential loss of tree growth in subsequent rotations." Although soils in the "high risk" category are considered likely to suffer reduced productivity if stumps are removed, stumping may be conducted

3 Stump removal has been associated with a slower recovery of vegetation in several studies (Smith and Wass 1991; Staaf and Olsson 1994; Kaye et al. 2008).

4 Brash is the above-ground parts of the tree not normally removed from site for sale after thinning or harvesting – that is, branches, tops of trees, small dead trees unacceptable for conventional timber processing, and conifer needles.

on those sites if nutrients are replaced through "remedial treatments" of wood ash or limestone. However, the cost of these materials, their impact on the carbon balance, their interactions with soil nitrogen availability, and the potential for nutrient runoff and streamwater acidification, as well as forest certification rules, must also be considered and may render remedial treatments too costly. Rendzinas (calcareous soils over chalk or limestone) are also considered to be at a high risk from stump harvesting because of the interactions between pH and iron availability. Sites considered to be at a medium risk of reduced soil fertility (e.g., podzolic brown earths and some types of gley or ironpan soils) may be stumped only if brash is retained. There are also restrictions on the timing of moving the brash mats used to support stumping equipment on medium-risk sites.

4. **Acidification** is the "removal of base cations (calcium, magnesium, sodium, and potassium), reducing soil buffering capacity and leading to increased soil and stream water acidification." The soil types at risk of acidification are similar to those at risk of reduced fertility since soil buffering capacity tends to be correlated with nutrient availability. Once again, the guidelines suggest that medium-risk sites can be stumped as long as brash is retained, and brash mats should not be moved until needles have been shed.

Sites are categorized as "high," "medium," or "low" risk for each of the four disturbance categories identified above. The assessments for each of these are then combined into an overall risk rating by soil type (Table 5 in Forestry Commission 2009b), and a summary of best practices is compiled to minimize site damage (Table 6 in Forestry Commission 2009b). On sites with a combined "medium" risk, for example, the guidelines suggest that stump harvesting be conducted only when the soil is relatively dry and better able to support machinery (i.e., between May and September) (Forestry Commission 2009b). In most cases, stump removal is considered to be inappropriate if the site falls into a "high" risk category, although there are some exceptions (e.g., mitigation of root disease infection, conversion to native vegetation).[5]

2.5 Guidelines for Stump Removal Practices

2.5.1 British Columbia The guidelines for British Columbia were developed for root disease amelioration, not for biomass harvesting. Once the level of root disease infection in a stand has been determined and the site sensitivity of the soil and terrain has been assessed, the instructions for carrying out stump removal are summarized as follows:

1. A silvicultural prescription should be prepared based on the degree of root disease infestation and the sensitivity of the site to soil disturbance during stump removal (Province of British Columbia 1995). Root removal by pushover logging or stumping should be prescribed only for sites with high levels of root disease and less sensitive soils (Norris et al. 1998).

5 UPM-Tilhill, the United Kingdom's leading forestry and timber harvesting company (UPM-Tilhill 2011), does not harvest both brash and stumps on the same forested site (Whitfield 2010), although the guidelines do not recommend against this on "low" risk sites (Forestry Commission 2009b).

2. Operations are best restricted to certain times of the year (i.e., dry season, or on snow or frozen soils) (Province of British Columbia 1995).
3. Proper equipment and techniques should be used to minimize soil disturbance. This includes lifting and rolling stumps rather than pushing them. Excavators with bucket and thumbclaw attachments are recommended rather than bulldozers (Province of British Columbia 1995).
4. If excavator stump removal is used, stumps should be placed upside-down in the stump hole. When pushover logging is used, a modified feller-buncher can drop stumps back in the stump hole. Alternatively, stumps should be bucked as close to the original stump hole as possible (Norris et al. 1998).
5. Operations should be inspected and monitored continuously to avoid excessive site or soil disturbance. Operations should be postponed during heavy rain or snow (Province of British Columbia 1995).

2.5.2 Finland Best practices for stump harvesting in Finland are described in a recent publication by TAPIO (2010). The following general recommendations for removing "energy wood" (in italics) have been combined with those developed specifically for stump harvesting:

1. *Schedule harvesting when the load-bearing capacity of the soil is high (i.e., when soil is frozen or in the dry season).*[6]
2. Clear logging slash from the regeneration area prior to harvesting stumps, except on semi-dry heaths, where slash should be cleared only enough to facilitate stump removal.[7]
3. Coarse woody debris to be left on-site can be moved to facilitate stump removal, *but ant hills and the nests of mammals and birds should be left undamaged, and large-diameter trees, whether standing live or dead or dead on the ground should be left undamaged during harvesting.*[8]
4. *Reinforce skid trails or patches of sensitive soils with a mat of logging residue or a light bridge–remove these materials after harvesting if they interfere with ditches or threaten water conservation but leave them if they've become embedded in the soil.*
5. Leave buffer strips of intact stumps around ditches (2–3 m), creeks, brooks and springs (3–5 m), along waterways (7–10 m), and around sites of natural interest and leave trees (3 m) to protect root systems and preserve water quality.
6. Try to avoid unnecessary soil exposure or forest floor displacement during stump removal, especially if site preparation is going to be performed in a separate step.
7. Shake the soil from the stump back into the stump hole, and avoid leaving holes deeper than 30 cm (measured from the top of the mineral soil).
8. Preserve as many mounds as possible to be used in planting, and try to mimic the effects of site preparation, such as scarification, mounding, etc.

6 Stump harvesting is restricted when the ground is frozen and snow covered (Laitila et al. 2008), so most stump harvesting probably occurs in the dry season.
7 The removal of logging slash is considered to be inappropriate for semi-dry heaths (see Table 3).
8 No definition of "large-diameter" is given.

9. Apply additional site preparation if the number of planting spots produced during stumping does not achieve the target planting density, or if planting spots are not evenly distributed throughout the stand.
10. Plant the site as soon as possible after stump removal to allow seedlings to establish before competing vegetation encroaches.
11. Pile stumps on a *level surface clear of loose rocks or vegetation, at least 3 m from leave trees (e.g., seed trees, shelterwood), and in a spot that does not impede road access.* The action of the sun, rain, and wind will remove excess soil and rocks and reduce the moisture content of the stumps. Each pile should be about 5 m × 5 m in size and can be covered with paper during the winter to maintain a low moisture content.
12. Unless there are no other alternatives nearby, stump piles should not be placed in ditches, which should be cleared of stumps after harvesting.

2.5.3 Sweden As mentioned above, the recently published recommendations for stump harvesting in Sweden are not yet available in English, and there is little guidance contained in Egnell et al. (2007) on stump removal operations beyond the following:

1. Retain stumps in buffers of 15 m along lakes and watercourses; do not pull stumps from harvested areas adjacent to lakes, streams, bogs, or ditches, or near leave trees, large stones, or anthills.
2. Use mats of coarse branches to protect the soil during stumping, particularly on soils with low to moderate load-bearing capacities.

2.5.4 United Kingdom The best practices for stump harvesting in the United Kingdom, once the site's sensitivity to stump removal has been assessed, are as follows (Forestry Commission 2009b):

1. Prepare a detailed site map or plan, which addresses all the constraints to stump removal; for example, biodiversity, historic environments, sensitive soils, health and safety concerns.
2. Lay brash mats on the forest floor surface during timber harvesting; the layout of these mats should take into consideration the subsequent stump removal process.
3. Leave stumps intact in a buffer strip around "high" risk soils or archaeological sites (5 m), along roadside ditches and drains (5 m) to prevent the delivery of sediment to streams, and along watercourses (5–20 m, depending on the width of the watercourse). Furthermore, retain stumps in a buffer (5 m) along the breaks of slopes (e.g., the upper edge of steep valley sides) to reduce the risk of slope failure.
4. On sites with a "medium" or "high" risk of soil degradation, remove stumps only when all brash is retained. Furthermore, conduct stump removal when brash mats are still green.
5. In order to ensure that brash mats are strong and supple enough to support heavy machinery during stumping, minimize the delay between stem and stump harvesting. If this is not possible, brash mats can be combined, when needle-free, into larger piles to increase their load bearing strength. To further protect the soil during stump removal, retain stumps beneath the brash mats on all extraction routes. Site rehabilitation practices should be used to eliminate any ruts produced during stump removal.

6. In most cases, conduct stump removal using a purpose-built harvesting head mounted to an excavator. The harvesting head should be used to split the stumps, thereby reducing contamination by rocks and soil. Use the excavator to shake the extracted stumps repeatedly, thereby minimizing the amount of soil moved off-site.
7. Store stumps at the roadside over the winter to allow rainfall and freeze-thaw action to remove remaining soil from the stumps. To prevent the export of nutrients and sediment to streams, stump piles should not sit on top of roadside drains.
8. To avoid spreading root rot inoculum, take care not to transfer soil between sites.

2.6 Guidelines for Stump Retention

2.6.1 British Columbia Stump removal in British Columbia is conducted to prevent the spread of root disease. The root diseases that typically infect tree stumps in British Columbia tend not to be infectious once the stumps have been pulled from the ground (Walmsley and Godbold 2010). Thus, stumps are generally inverted and replaced in the hole from which they were pulled (Norris et al. 1998; W. Chapman – B.C. Ministry of Forests, Lands and Natural Resources, pers. comm., Jan. 21, 2011). As a result, stump retention guidelines have not been necessary, to date. As mentioned above, however, Norris et al. (1998) suggested that it should be a particular priority to retain stumps on sites with thin forest floors and low levels of soil organic matter. Furthermore, Norris et al. (1998) suggested that stumps should not be treated as coarse woody debris: instead, they recommended that coarse woody debris should be left in addition to stumps. This suggestion should be kept in mind if stump retention guidelines for British Columbia are required in the future.

2.6.2 Finland The Finnish stump harvesting guidelines suggest that a range of stumps should be left on the harvested site to conserve biodiversity and soil quality. The stump retention guidelines are as follows:

- on sites with clay or loamy soils, at least 50 stumps should retained per hectare[9];
- most of the retained stumps should have a diameter less than 15 cm[10];
- approximately 25 retained stumps per hectare should have a diameter of more than 15 cm;
- retained stumps should be distributed evenly across the harvested area;
- retained stumps should represent a variety of tree species; and
- fresh cut but unsound stumps should be removed from all but buffer areas to reduce the spread of root disease.[11]

9 There appears to be no lower limit set for coarser textured soils, although Stupak et al. (2008) indicated that the lower limit was 20 stumps per hectare.

10 This is probably for two reasons: (1) smaller stumps have a higher proportion of nutrient-rich bark (Walmsley and Godbold 2010), and (2) it is not cost-effective to remove small stumps (AEBIOM 2007).

11 In practice, stump harvesting operations in Finland tend to leave approximately 25% of the stumps in the ground because only the largest stumps are pulled (UPM-OPET 2003). Furthermore, given that spruce stumps are more easily removed from the ground and have a relatively high wood content, most of the retained stumps consist of hardwoods and pine (Tekes 2004).

2.6.3 Sweden The recommendations in Egnell et al. (2007) suggest that stump removal operations always retain some stumps and "consider the biological value of those that are left." The recommendations also suggest that a greater quantity and quality of above-ground coarse woody debris be retained on sites where stumps are harvested (Egnell et al. 2007).[12] According to Stupak et al. (2008), retention of some stumps with a diameter < 20 cm and some stumps with a diameter > 60 cm is recommended.

2.6.4 United Kingdom The stump removal guidelines for the United Kingdom recommend that stumps be left under brash traffic pathways, which apparently corresponds to about 20–30% of the ground surface (Forestry Commission 2009b). Retaining stumps under brash mats and in buffer areas is expected to result in the retention of about 30–40% undisturbed ground. The guidelines also suggest that rotten stumps be retained for wildlife value, but there is no indication whether this refers to fresh-cut stumps or only those present prior to harvesting. According to Walmsley and Godbold (2010), the United Kingdom Woodland Assurance Standard suggests a minimum of 20 m^3/ha (5–10% of the average stand volume) of deadwood be retained across a clearcut as a whole. However, these guidelines do not consider stump biomass (Walmsley and Godbold 2010).

2.7 Summary and Issues Raised

Not surprisingly, the driest, wettest, and most nutrient-poor ecosystems are generally considered to be most sensitive to stump removal. However, each jurisdiction identifies sensitive sites in a different way: soil type is the primary means of identifying sensitive areas in the United Kingdom, while ecosystem type is used for the same purpose in Finland. In British Columbia, sensitivity is determined at the stand level by using information on soil properties, topography, and biogeoclimatic zone to assess the risk of several types of hazard. The risks of each hazard are then combined to assess site suitability for stump removal. Guidelines in the United Kingdom are similar to those in British Columbia in that the combined risk of several types of hazard is used to guide best practices for stump removal at a given site. The Finnish guidelines for identifying sensitive sites are much less prescriptive and somewhat vague (e.g., steep slopes and large diameters are not defined).

The amount of guidance on stump removal practices also varies considerably among jurisdictions, but guidelines from Finland and the United Kingdom are the most detailed. As well, stump retention guidelines diverge widely. In Finland, the minimum number of retained stumps is 20/ha (50/ha on finer-textured soils). The guidelines further recommend that retained stumps be evenly distributed throughout the stand and represent a range of species and stump sizes. In practice, however, it appears that small pine and hardwood stumps are generally retained at the expense of large spruce stumps. In the United Kingdom, stump retention guidelines are based not on the number of stumps retained but on the area of the clearcut that is left undisturbed by stump removal. Given that stumps are retained under slash-

12 In reality, there would be little opportunity to compensate for stump removal with large pieces of woody debris, given that stumps typically constitute about 80% of the total coarse woody debris in Swedish managed forests (Egnell et al. 2007). Furthermore, it would be difficult to justify retaining large pieces of freshly cut wood in exchange for stump biomass, which is more difficult, expensive, and potentially damaging to harvest.

covered extraction trails, the distribution of retained stumps will be more clustered. Presumably, extraction trails avoid large stumps, which would inhibit the movement of forestry equipment.

2.7.1 Stand productivity after stump harvesting The long-term implications of stump harvesting on soil quality remain largely unknown (Egnell et al. 2007; Forestry Commission 2009b), partly because stumping treatments are often confounded by differences in other factors such as disease incidence, levels of soil disturbance, and species responses. Stump removal has been shown to alter and even improve nutrient availability and tree growth and survival in the short term under some conditions (e.g., Smith and Wass 1991; Morrison et al. 1998; Hope 2007; Vasaitis et al. 2008; Newsome et al. 2010), but it is unclear whether short-term improvements in productivity can be maintained over time (Hope 2007). Ten years after harvesting stumps from a site in Sweden, lower exchangeable levels of calcium were measured in the soil (Egnell et al. 2007). This may be related to the removal of calcium-rich stump bark or to accelerated leaching losses of nutrients, but it is unclear whether tree growth reductions were also observed at the site. Given that much of the research published in English on the implications of stump harvesting on soil nutrients and stand productivity originates from British Columbia and the U.S. Pacific Northwest, a closer examination of temporal trends using meta-analysis or graphical techniques (see Vasaitiis et al. 2008) may yield some useful information (Table 6). However, many of these trials were established on sites with high rates of root disease, and as a result, the effects of stump removal on the productivity of these stands will not apply to sites with low or no incidence of root disease. Furthermore, stumps were often retained on-site in these trials, and as a result, treatment effects will not accurately reflect the effects of stump harvesting for bioenergy.

Stumps can contain a large fraction of the organic matter pool in some cut stands, and their removal causes an immediate reduction in the carbon stock of a given site (Norris et al. 1998). Perhaps more importantly, however, stumping can cause greater soil mixing and exposure of deeper horizons (Standish et al. 1988; Davis and Wells 1994; Quesnel and Curran 2000), which, in turn, is expected to stimulate mineralization and leaching losses of soil carbon (Egnell et al. 2007; Forestry Commission 2009b; Walmsley and Godbold 2010). The impact of stump removal on soil carbon is an important issue because losses of soil carbon have implications for the physical (e.g., aeration porosity, aggregate stability), chemical (e.g., cation exchange capacity), and biological (e.g., habitat quality) properties of soils (Fisher and Binkley 2000; Bot and Benites 2005). Stump biomass can be considered a truly renewable resource only if harvesting-induced changes in soil carbon do not compromise the future productivity of the stand. Furthermore, there is significant concern that the soil carbon losses associated with stump harvesting exceed the savings in carbon emissions that are achieved by replacing fossil fuels with stump biomass (Walmsley and Godbold 2010). At this point, the effect of stump harvesting on soil carbon pools remains one of the most critical knowledge gaps (Egnell et al. 2007; Forestry Commission 2009b; Walmsley and Godbold 2010).

TABLE 6 *Stumping trials with published soil carbon and nutrient data, and tree growth and/or foliar nutrient data, from North America*[a]

Site	Year	Soil data[b]	Tree data	Key references
Canada (British Columbia)				
Adams Lake	1992	C, N, and other nutrients	Height, diameter, foliar nutrients	Hope 2007
Banon FSR	2007	–	Height, diameter	Courtin 2010
Gates	1980	C, N	Height, diameter, foliar nutrients	Smith and Wass 1991; Wass and Senyk 1999
Hidden Lake	1993	C, N, and other nutrients	Height, diameter, foliar nutrients	Hope 2007
Ice Road	1996	–	Height, diameter	Newsome et al. 2010
Lemieux Creek	2002	–	Height, diameter, foliar nutrients	Kiiskila 2005
Lower Campbell Lake	2007	–	Height, diameter	Courtin 2010
Malakwa	1991 and 1992	C, N, and other nutrients	Height, diameter, foliar nutrients	Hope 2007
Marl Creek	1983	C, N	Height, diameter, foliar nutrients	Smith and Wass 1994
Mount Seven	1995	–	Height, diameter	Newsome et al. 2010
Phoenix	1980	C, N	Height, diameter, foliar nutrients	Smith and Wass 1991; Wass and Senyk 1999
Sechelt (Trout Lake)	2006	–	Height, diameter	Courtin 2010
Shawnigan Lake	1985	C, N	Height, diameter	Wass and Smith 1997
Skimikin	1968	–	Height, diameter	Morrison et al. 1988
Timberlands Rd	2007	–	Height, diameter	Courtin 2010
Trestle Lake	2006	–	Height, diameter	Courtin 2010
United States				
Apiary, Oreg.	1978	C, N	Height, diameter, foliar N	Thies and Westlind 2005; Zabowski et al. 2008
Bradford, Fla.	1981	C, N, S	Height, diameter	Johnson et al. 2002
Gates, Oreg.	1980	C, N	Height, diameter, foliar N	Thies and Westlind 2005; Zabowski et al. 2008
Glenwood, Wash.	1971	–	Height, diameter	Roth et al. 2000
Hoodsport, Wash.	1976	C, N	Height, diameter, foliar N	Thies and Westlind 2005; Zabowski et al. 2008
La Grande, Oreg.	1978	C, N	Height, diameter, foliar N	Thies and Westlind 2005; Zabowski et al. 2008
Priest River, Idaho	1991	–	Height, diameter, tissue N	Page-Dumroese et al. 1998
Sweethome, Oreg.	1980	C, N	Height, diameter, foliar N	Thies et al. 1994; Thies and Westlind 2005; Zabowski et al. 2008

a Studies from Europe and New Zealand are not included because none of those in English included soil chemical analyses. Of the studies from Europe and New Zealand that measured tree growth after stump removal, few were published in English, were available as complete manuscripts, or reported data in a comparable format to that of North American studies.

b C: carbon; N: nitrogen; S: sulphur

The impact of stump harvesting on soil carbon and nutrients will probably remain a question for some time because high spatial and temporal variability generally makes it difficult to detect treatment differences (Yanai et al. 2003; Johnson et al. 2007), and rotation lengths are long. In addition, site preparation treatments applied after stump removal can mask the effects of stump harvesting (Hope 2007). Until more data are available, the Forestry Commission (2009b) in the United Kingdom has assumed that the scale of carbon lost from the soil following stump harvesting is directly proportional to pre-harvest soil carbon stocks. According to this system, peatland and bog soils are considered to be at "high risk" of soil carbon loss, while soils with lower carbon contents (e.g., brown earths [Brunisols], skeletal soils, and some podzolic soils), are considered to be at "low risk"; however, the organic matter stored in low-carbon soils can be more sensitive to disturbance (Thiffault et al. 2006). Furthermore, low-carbon soils are often most able to retain dissolved organic carbon that is leached through the soil profile (Ussiri and Johnson 2004). A recent meta-analysis that examined the effect of timber harvesting on soil carbon pools in temperate forests indicated that inceptisols (Brunisols) lost more mineral soil carbon after logging than any other soil type (Nave et al. 2010). Thus, it would be appropriate to restrict stump harvesting in low-carbon soils as well.

Previous studies have suggested that the effects of whole-tree harvesting tend to vary by region and with the tree species composition of the stand. For example, the results of the North American–wide long-term soil productivity study suggest that less of the carbon in above-ground logging residues is retained in soil organic matter on sites with warmer climates compared to sites with wetter and cooler climates (Powers et al. 2005). A meta-analysis by Johnson and Curtis (2001) demonstrated that soil carbon stocks in coniferous stands typically benefit more from residue retention than those in mixedwood or deciduous stands. At this point, however, there are probably insufficient data to conduct a similar analysis on the implications of stump removal on soil carbon pools. In the 13 stumping trials in North America with published soil carbon data (Table 6), stumps were removed or windrowed on seven sites and were retained in or near the stump hole on five sites. Details of post-removal stump placement were not provided for the remaining site.

The impact of stump harvesting on the physical properties of the soil and the implications for tree growth should not be ignored. Several studies in British Columbia and the U.S. Pacific Northwest have investigated the effects of stump removal on levels of soil disturbance and soil compaction immediately after harvesting (e.g., Smith and Wass 1991; 1994; Sturrock et al. 1994; Wass and Smith 1997; Page-Dumroese et al. 1998; Quesnel and Curran 2000; Hope 2007), but few have monitored changes in soil physical properties through time. Hope (2007) found that treatment differences in bulk density disappeared within 10 years of stump removal, and concluded that the increased levels of bulk density caused by stumping on moderately coarse sites (sandy loam to loamy sand) was not sufficient to reduce tree growth. However, on a 3-year-old cutover with finer-textured soil (silt loam) in northern Idaho, soil compaction from stump removal appeared to have reduced the growth of Douglas-fir (*Pseudotsuga menziesii*) and western white pine (*Pinus monticola*) seedlings (Page-Dumroese et al. 1998). Similarly, the height and diameter growth of naturally regenerated interior spruce was reduced on a 10-year-old pushover-harvested site in the southern interior of British

Columbia (Mount Seven, on silt loam to loam) (Newsome et al. 2010). The authors postulated that this was caused by treatment differences in the level of soil compaction. Site preparation and stand tending practices in Europe are more intensive than those commonly employed in British Columbia, and as a result, the soil disturbance associated with stump harvesting may be of less concern in Europe. Thus, it is critical to develop stump harvesting guidelines that are consistent with the harvesting practices, management philosophies, and ecological conditions of British Columbia.

2.7.2 Simplification of method for assessing sensitivity to stump removal The extant guidelines for assessing site sensitivity to stump removal in British Columbia are contained in three different publications, and the methods of assessing site sensitivity to soil degradation have changed since the *Root Disease Management Guidebook* was published (Province of British Columbia 1995; 2000). In order to facilitate their use for stump harvesting, the guidelines would need to be updated and published in a single document. Furthermore, the site sensitivity assessment process is more complex than in other jurisdictions, thereby reflecting the complexity of British Columbia's geography and ecology. While there appears to be potential for simplification given that several variables (e.g., slope, soil texture) are used to assess multiple hazards (Table 4), earlier attempts to do so have failed due to the complexity mentioned above (M. Curran – B.C. Ministry of Forests, Lands and Natural Resources, pers. comm., Oct. 2011).

2.7.3 Retention guidelines To date, stump retention guidelines have been unnecessary in British Columbia because pulled stumps are usually left on-site. If stump harvesting for bioenergy proceeds in this province, however, stump retention guidelines that consider the following questions will be required:

1. Do stumps and coarse woody debris perform different ecological roles, or can coarse woody debris be substituted for stumps?
2. Does the ecological value of stumps from different tree species vary (e.g., in terms of rarity, dependent species, longevity)?
3. Is it important to ensure that high-carbon, long-lasting (large) stumps are retained as well as nutrient-rich (small) stumps?
4. Does harvesting of trees with "plate-like" root systems (e.g., spruce) cause more nutrient depletion and soil disturbance than harvesting of trees with tap roots (e.g., pine)?
5. How should retained stumps be distributed across the cutblock and across the landscape?
6. What is the lower limit for stump retention and does it vary by region, biogeoclimatic zone, pre-harvest stand density, or other factors?
7. What is more important and operationally feasible: retaining a diversity of stump sizes and species or retaining a certain number, percentage, or volume of stumps?
8. What are the indicators that stump retention guidelines are being effective?
9. How will the efficacy of stump retention guidelines be monitored and by whom?

The cost of producing forest biomass depends on a number of factors, including the steepness of the terrain from which the material is harvested, the distance the material must be transported, the efficiency of the storage and drying process, the degree of mechanization, the type and size of machines used in every step of the process, and the costs of labour (AEBIOM 2007). In Finland, where the stump harvesting industry is most well developed, a sustained increase in the use of forest biomass for energy production is predicated on reductions in production costs, improvements in fuel quality, and increases in efficiency and reliability of delivery systems (Hakkila 2006). Although the techniques used to harvest stumps in Scandinavia today are essentially the same as those employed in the 1970s (Egnell et al. 2007), considerable investments are being made to improve the cost-effectiveness of stump removal by increasing the efficiency of stump harvesting technology (Hakkila 2006).

To simplify the discussion of technological improvements in the harvesting and utilization of stump biomass, the process has been divided into the following steps:

- harvesting and transport within the cutblock;
- transportation and comminution; and
- utilization.

3.1 Harvesting and Transport within the Cutblock

Stump harvesting techniques in British Columbia, Finland, Sweden, and the United Kingdom are relatively similar. In British Columbia, Sturrock (2000) recommends the use of "excavators with a standard bucket and a hydraulically operated gripping thumb" to pull stumps or push-fall trees. Given that stumps are typically left inverted in the hole from which they were pulled, transport through the cutblock is usually not required. After pushover logging, however, skidders can be used to carry entire trees back to the landing for stump removal (Davis and Machmer 1998), although this is not a common practice due to logistical constraints (M. Curran – B.C. Ministry of Forests, Lands and Natural Resources, pers. comm., Oct. 2011). In Finland, Sweden, and the United Kingdom, the most basic stump harvesting system is comprised of an excavator with a purpose-built stump harvesting head, which is used to pull, split, and shake stumps, and a forwarder, which is used to move the stumps to the roadside for storage and subsequent removal (Tekes 2004; AEBIOM 2007; Forestry Commission 2009b). Harvesting heads include various Pallari models (www.tervolankonepaja.fi/en), the "Kantokunkku" (www.youtube.com/watch?v=TBoonWoiofE), the Alto, the Steelpa, and the Hercules (Lindroos et al. 2010a). Thus, the main differences between the stump harvesting equipment in British Columbia and Europe are the use of purpose-built stump harvesting heads and the use of forwarders to transport stumps out of the cutblock.

3.1.1 Stump removal and site preparation In Europe, site preparation is usually combined with stump wood extraction and is often performed using a purpose-built mounding blade or backplate attached to the stump harvesting head (Mitchell 2009; Rabinowitsch-Jokinen and Vanha-Majama 2010). The combination of stump removal and site preparation can be viewed at www.youtube.com/watch?v=ZoVuloXx_oc. Direct seeding can also be carried out using seeding equipment connected to the stump puller. This is most often done on pine-dominated stands (UPM-OPET 2003).

3.1.2 Innovations in harvesting heads Spruce stumps are more easily pulled from the ground than are pine stumps because the coarse roots of spruce tend to remain near the soil surface (Tekes 2004). However, work is under way to develop technology that would facilitate pine stump harvesting. Laitila (2008) recently compared the utility of different stump harvesting heads, including the Kantokkunku, the Pallari KH160, and stump drills, for the removal of pine stumps, but the conclusions of the study are not yet available to us because the report is available only in Finnish.

Cylinder-shaped drills can be effective at pulling trees with long tap roots, such as pines or poplars (Laitila 2008). Such drills are widely used on plantations in Italy, Hungary, and the Balkans (Spinelli et al. 2005). In Sweden, a newly designed 70-cm diameter cylindrical stump drill was tested on both pine and spruce stumps, but the yield of wood was lower than normal because lateral roots are severed by the drill (von Hofsten and Nordèn 2007), and the bit, which is essentially a giant hole saw, was easily damaged by coarse fragments (O. Läspä – Metla (The Finnish Forest Research Institute), pers. comm., Mar. 3, 2011). Of course, cylindrical drills would not be appropriate for treating root disease–infected stands because they leave coarse roots intact in the soil.

In Finland, it is currently standard practice to harvest stumps only at final felling because of the potential for damaging the residual stand during stump removal at thinning (O. Läspä – Metla (The Finnish Forest Research Institute), pers. comm., Mar. 3, 2011). Although stump drills are not currently being used in Finland, a conventional John Deere stump drill was recently tested, with limited success, as a method of harvesting spruce stumps during intermediate thinning operations (Läspä 2010; O. Läspä – Metla (The Finnish Forest Research Institute), pers. comm., Mar. 3, 2011). To view an example of a conventional stump drill, go to www.cbi-inc.com/uploads/CBI_Stump_Screw_low_res.pdf.

3.1.3 Innovations in forwarders Although crawler-excavators are effective at stump removal, they are designed mainly for digging and are not capable of moving quickly across rough terrain. In addition, the vibrations caused when stumps are shaken to remove soil can be hazardous to excavator operators (Lindroos et al. 2010a). To address these issues, wheeled stump "harwarders," which use the cabin and crane of an excavator and the undercarriage of a forwarder, are being used on an experimental basis in Finland to carry out both uprooting and off-road transport of stumps (Tekes 2004; Lindroos et al. 2010a).

3.2 Transportation and Comminution

The costs of transporting forest biomass are extremely high because the materials are bulky and difficult to load efficiently (AEBIOM 2007; Lindroos et al. 2010b; von Hofsten and Granlund 2010). This is a particular problem for oddly shaped root and stump systems, which do not compact well, although splitting stumps at the time of harvest ameliorates this problem to some degree (Mitchell 2009). After drying for a year at the roadside, stumps are transported to the terminal or end-use facility by truck-and-trailer units specifically designed for carrying uncomminuted biomass (Tekes 2004; Laitila et al. 2008; Forestry Commission 2009b). Transportation distances do not typically exceed 100 km in Finland (Flynn and Kumar 2005).

Stump and root biomass must be comminuted, or broken into smaller pieces (usually 10–15 cm in diameter) (Flynn and Kumar 2005), before they can be used in bioenergy plants. Comminution improves the fuel properties of the biomass by making it easier to handle, more homogeneous, and denser (Johansson et al. 2006, cited by Lindholm et al. 2010). Thus, comminution at the roadside could substantially reduce the costs of transporting stump biomass (Bradley 2007; Lindroos et al. 2010b). However, contamination by soil and rocks generally precludes the use of roadside chippers typically employed for the comminution of forest residues (e.g., www.mobilechipper.com) because chippers are easily damaged by contaminants (Lindroos et al. 2010b). Although split and dried stumps shed significant quantities of dirt and stones while piled at the roadside (Tekes 2004; AEBIOM 2007; Forestry Commission 2009b), they are inevitably more contaminated than forest biomass harvested from above ground. In fact, one of the most critical barriers to the use of stumps and roots for biofuel in the past has been contamination with soil and stones (AEBIOM 2007). The development of large and more robust stationary crushers was a major breakthrough in the expansion of the stump biomass industry (Hakkila 2006; AEBIOM 2007; Roser et al. 2008). Nonetheless, only a few heavy on-site crushers have been in use because of the high cost of investment (Tekes 2004).

Recently, effective mobile crushers suitable for the comminution of stumps have been introduced (e.g., Hakkila 2003; Asikainen 2010; Lindroos et al. 2010b: www.cbi-inc.com/library/pdfs/CBI_Magnum_Force_6800P_Brochure.pdf). In a recent Swedish study, a roadside crusher equipped with a slow-rotation, high-torque grinder attached to a drum screen that separates stump wood chips from soil contaminants reduced transportation costs by at least 15%; furthermore, contamination fell from 5–7% to 1–2% of the total chip mass (von Hofsten and Granlund 2010). Besides reducing transportation expenses, such a system could improve the cost-effectiveness of stump harvesting by reducing the amount of time required to shake soil and stones free from stumps during the extraction phase and by lowering the amount of ash produced during combustion. This ash is often landfilled because it is high in "impurities" (von Hofsten and Granlund 2010). Buyers of forest biomass will not pay a premium for stump chips with high levels of contaminants because these impurities reduce boiler efficiency. In fact, many boilers are incapable of utilizing stump chips with contaminants (Mitchell 2009). Despite the development of roadside crushers, stumps will probably always be crushed at the bioenergy plant to some extent because, unlike intact stumps, wood chips do not store well. Microbial decay can cause the quality of stump wood chips

to decline rapidly and even lead to spontaneous combustion (Johansson et al. 2006). One of the reasons why stump chips are becoming a more popular feedstock at the bioenergy plant is that intact stumps store well and absorb less moisture over the winter than other forms of forest biomass (AEBIOM 2007).

3.3 Utilization

Another major breakthrough that has facilitated the establishment of the stump biomass industry in Finland was the development of power plants that use fluidized bed boiler technology that is capable of using biofuels with uneven particle sizes, high moisture contents, or variable qualities (Hakkila 2006; Laitila 2008). In fluidized bed boilers, combustion occurs in a hot bed of sand, which stabilizes the gasification process despite fluctuations in fuel properties (Hakkila 2006).

Peat is often co-fired with wood fuels in these plants in order to standardize the moisture content of the fuel and to provide a constant energy supply when stores of wood chips are low (Hakkila 2006). The Alholmens Kraft biofuel plant on the west coast of Finland, for example, typically uses a 50/50 mix of wood and peat (Hakkila 2006). The use of peat as an energy source is problematic, however, because it is not considered to be a renewable energy source by the European Commission (AEBIOM 2010), and the maintenance of undisturbed peatlands is considered to be a priority for greenhouse gas management (International Peat Society 2008). Thus, attempting to reduce greenhouse gas emissions by increasing the use of forest biomass through co-combustion with peat could be seen as counter-productive.

3.4 Future Directions

Finland is hoping that the export of new technologies around the world will help the country recover some of the massive investments it is making in improving the efficiency of biomass harvesting, transport, comminution, and utilization (Hakkila 2006). However, in order to fully understand the logistics of establishing a stump biomass harvesting industry in British Columbia, an in-depth analysis is required to address investment costs, stump biomass availability, and transferability of European harvesting systems to different species, forest types, and geographies. In-depth life cycle analyses are also required to determine if such an industry could actually make money or reduce greenhouse gas emissions in British Columbia, where travel distances, management practices, and existing infrastructure are very different from those in Europe. Laitila (2006) has developed an Excel-based tool to perform sensitivity analyses and estimate the costs of procuring forest biomass in Finland. He has made available a calculator that is specific for stump harvesting (J. Laitila – Metla (The Finnish Forest Research Institute), pers. comm., Mar. 2, 2011). With his permission, this tool could probably be modified to initiate such a discussion in British Columbia.

4 STUMP CONTENT OF ROADSIDE DEBRIS PILES

There is a general consensus that the stump content of roadside debris piles in British Columbia is very low (i.e., between zero and 10%) (B. Markstrom – B.C. Ministry of Natural Resource Operations, pers. comm., Feb. 21, 2011; E. Armstrong – B.C. Ministry of Forests, Lands and Natural Resources, pers. comm., Feb. 21, 2011). Even after stump removal treatments, most pulled stumps remain in the stand (W. Chapman – B.C. Ministry of Forests, Lands and Natural Resources, pers. comm., Jan. 21, 2011). It is also important to note that stumps pulled for root rot treatments may not be a good source of forest biomass (Standish et al. 1988) because they tend to be of lower fuel quality (Vasaitis et al. 2008).

5 METHODS OF ESTIMATING THE VOLUME AND BIOMASS OF TREE STUMPS AND ROOTS

Stumps and coarse roots can represent 10–45% of total tree biomass (e.g., Comeau and Kimmins 1989; AEBIOM 2007; Walmsley and Godbold 2010), and the fuel yield from stumps can be as high as that from above-ground residues (Tekes 2004). Accurate measurements of stump volume and biomass are very difficult to obtain (Laitila et al. 2008), although the topic has received considerable interest over the years (e.g., Gholz et al. 1979; Raile 1982; Vogt et al. 1996; Repola et al. 2007). The basics are presented below.

5.1 Above-ground Stump Volume

Ground sampling in Canada's National Forest Inventory plots includes an assessment of the above-ground volume of all stumps with a diameter of 10 cm or greater (Natural Resources Canada 2008). For each stump, the top diameter, height, species, and decay class are recorded, and stump volume is calculated using the formula for a cylinder (Natural Resources Canada 2004):

$$\text{Stump volume} = \pi \cdot (d/2)^2 \cdot h$$

where d = stump top diameter (inside bark) and h = stump height

This simple method of estimating stump volume is widely used around the world (e.g. Jenkins et al. 2003; ForestBIOTA 2006; Samalca 2007; Teissier du Cros and Lopez 2009), although some jurisdictions use stump top diameter (outside bark) in calculations. Furthermore, some jurisdictions use correction factors that adjust the value of stump volume calculated using this equation to accommodate species differences in taper curve or bark morphology (e.g., Rabinowitsch-Jokinen and Vanha-Majamaa 2010).

5.2 Above-ground Stump Biomass

For inventories of deadwood, stump volume data are usually sufficient, but stump biomass data are required to assess forest carbon stocks or to estimate the quantity of stumps available for bioenergy. Above-ground stump biomass is typically calculated according to the following formula:

$$\text{Stump biomass} = \text{stump volume} \cdot \text{wood density (or specific gravity)}$$

Stump biomass can be calculated separately for stump wood and bark using volume and wood density values for each; total stump biomass is then calculated as the sum of stump wood and bark biomass (Jenkins et al. 2003). Published values of the density or specific gravity (density relative to water) of wood and bark can be extracted from a variety of sources, including Gonzalez (1990), Jenkins et al. (2003), and Miles and Smith (2009). However, wood density can vary with stem diameter, site index, stand age, and stand density (Parminter 1997; Repola et al. 2007; Skovsgaard et al. 2010). To accommodate differences in wood density when estimating the biomass of different tree components, some studies have developed species-specific equations to predict wood density with diameter, tree age, and/or distance along the stem or root (e.g., Repola et al. 2007; Skovsgaard et al. 2010).

Numerous techniques have also been developed to estimate the volume or biomass of stumps in uncut stands. These include the use of species-specific equations that estimate stump volume from diameter at breast height (dbh) (e.g., Raile 1982) or stump biomass from values of whole-bole biomass (Heath et al. 2009). Such methods would be particularly useful when estimating the stump fuel potential of uncut stands or the economic implications of cutting at various stump heights (Raile 1982). For the Canadian Forest Service's current Carbon Budget Model (CBM-CFS3), stump biomass is estimated at the stand level using merchantable volume-to-biomass equations developed by Boudewyn et al. (2007), and stump height and top dimensions specific to each province (C. Smyth – Natural Resources Canada, pers. comm., Jan. 27, 2011).

Once stump biomass is determined, the carbon content of the stump can be calculated by multiplying stump biomass by 0.5 (i.e., the approximate concentration of carbon in organic matter) (Hagemann et al. 2010).

5.3 Root Biomass

Coarse root biomass is allometrically related to stem biomass (Niklas and Enquist 2002; Li et al. 2003). Numerous studies have taken advantage of this relationship to develop equations for the prediction of below-ground root biomass from above-ground tree measurements available at a national scale. Given that root biomass is difficult and time-consuming to quantify, however, these relationships are often developed from limited data sets, from archival data, or from previously published work. For example, Levy et al. (2004) used data from 1360 trees sampled across Great Britain in the 1960s to calculate species-specific root-to-shoot ratios that will be used to revise national carbon inventories (Levy et al. 2004). Skovsgaard et al. (2010) used data from 114 trees sampled across Denmark to develop equations that estimate the below-ground biomass of Norway spruce using dbh, tree height, site $index_{50}$, stand top height, and mean stand diameter data. Repola et al. (2007) used data from 31 – 39 trees per species to develop equations that estimate Norway spruce, Scots pine, or birch (*Betula* species) stump and root biomass from dbh, and in some cases, tree height. In the United States, root biomass estimates for forest carbon inventories are calculated from dbh data, using equations that were produced by combining estimated values from previously published equations (Jenkins et al. 2003; Heath et al. 2009). For the CBM-CFS3, root biomass is estimated from above-ground biomass using separate equations for hardwoods and softwoods. These equations were developed using data from 49 root biomass studies from around the world (Li et al. 2003; C. Smyth – Natural Resources Canada, pers. comm., Jan. 27, 2011).

The factors governing root biomass are diverse and complex (e.g., site and stand conditions, tree species, management practices) (Li et al. 2003; Levy et al. 2004; Skovsgaard et al. 2010). Thus, equations that were developed to estimate root biomass on a national scale may not be appropriate for use on a stand scale. However, a number of equations have been developed to estimate coarse root biomass from dbh or basal area for common tree species in British Columbia (e.g., Comeau and Kimmins 1989; Thies and Cunningham 1996; Omdal et al. 2001), and these equations might be applicable to other similar stands (e.g., Wei et al. 1997).

6 CONCLUSIONS

Stump biomass represents a significant potential source of bioenergy in British Columbia. Given that few stumps are removed to the roadside during regular timber harvesting operations or root disease treatments, stump harvesting for biomass would entail a significant change in current forest management practices. In order to transport and use stumps effectively, significant investment in harvesting, comminution, and gasification technologies will also be required. Furthermore, there are numerous ecological, economic, political, and social barriers to overcome before industrial-scale stump harvesting could be seriously considered in British Columbia. If stump harvesting is actively pursued in British Columbia, the existing stump removal guidelines, which were developed in the context of root rot disease management and not bioenergy production, will need to be revised and updated. Stump harvesting guidelines from Sweden, Finland, and the United Kingdom would be useful examples while completing this task. Finally, accurate methods of estimating the quantity of stump and coarse root biomass in different stand types will need to be developed or adapted in order to efficiently plan stump harvesting operations.

Although industrial stump harvesting is proceeding in some European countries, there are few well-designed, field-based studies in which the effects of stump removal on soil carbon and nutrients have been examined. As a result, the implications of stump harvesting on greenhouse gas emissions and long-term soil productivity remain largely unknown (e.g., Egnell et al. 2007; Hope 2007; Forestry Commission 2009b; Lindolm et al. 2010). The results of modelling exercises that examine the implications of stump removal on greenhouse gas emissions and soil carbon stocks vary widely. For example, Melin et al. (2010) concluded that the combustion of stumps harvested at a medium intensity, in which 70% of all stumps are removed at final felling, results in significant reductions in carbon dioxide (CO_2) emissions compared to the combustion of coal. This conclusion was based on the assumption that all of the carbon bound in stump biomass will be released into the atmosphere within 100 years (Melin et al. 2010). However, the study fails to account for the fact that wood can endure in and on the ground for several centuries (Feller 2003) and that a portion of this carbon will be incorporated into the soil organic matter, particularly under cool, moist conditions (Powers et al. 2005), while the soil disturbance associated with stump removal is expected to accelerate the decay of soil carbon (Walmsley and Godbold 2010). Nonetheless, Whitfield (2010) proposed that the global warming potential (kg CO_2

released per KWh produced) of stump biomass is significantly less than that of coal, even if all soil carbon is lost from stump-harvested sites. In contrast, a recent study commissioned by the Finnish Ministry of the Environment concluded that most modelling studies and carbon accounting protocols overestimate the benefits of producing energy from stump biomass because they fail to account for reductions in the carbon sink capacity of forest soils following stump extraction (Liski et al. 2011, cited in SYKE 2011). The authors concluded that stump harvesting would undermine Finland's efforts to reduce greenhouse gas emissions, and they suggested that the extraction and combustion of small-diameter materials (e.g., generated during whole-tree harvesting or thinning operations) would be most effective in achieving Finland's greenhouse gas emissions targets (Liski et al. 2011). This publication is available only in Finnish, so it is not possible, at this date, to determine whether the assumptions of the study are reasonable.

To conclude, Benjamin (2010; p. 7) summarized the costs and benefits of stump harvesting in Maine as follows:

> *At this time it is safe to assume that the cost and energy required to harvest, clean, transport, and process the stump and root system far exceeds the current demand and cost structure from industries in Maine. In addition, since stump and root systems play a vital role in nutrient cycling, contribute significantly to nutrient retention, increase soil stability against erosion, and retain soil structure, the environmental and economic aspects of stump and root harvesting may preclude their present utilization.*

Now is the time to determine whether stump harvesting is a viable option for British Columbia by making clear to decision-makers the environmental risks associated with increased soil disturbance, loss of nutrients and organic matter, and further removal of coarse woody materials.

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